METEORS WITHOUT SODIUM

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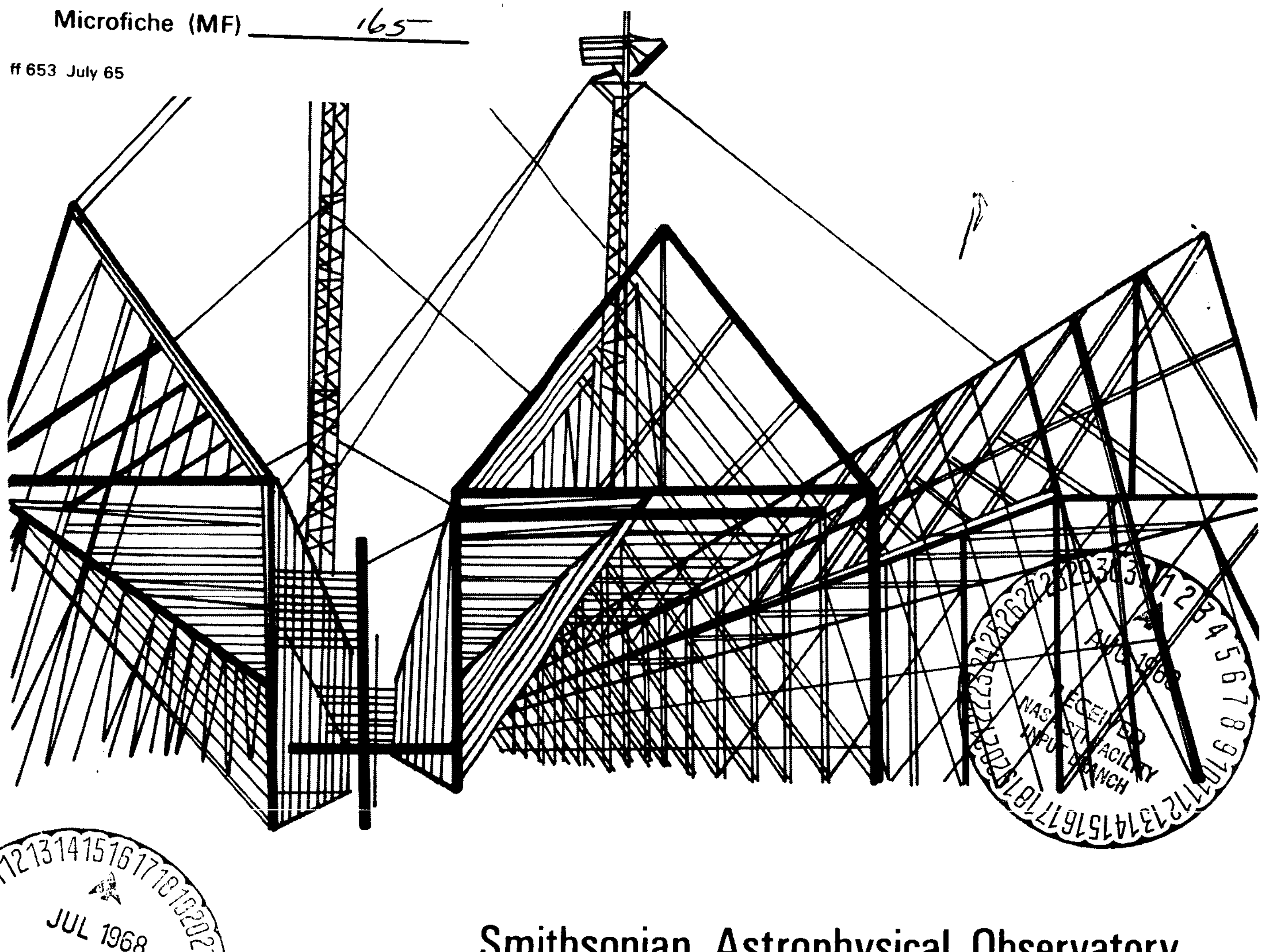

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ABSTRACT

Meteor spectra consisting of Fe radiation, but without D lines of Na I, have, in the past, been attributed to iron-nickel meteoroids. One such case, a meteor observed and analyzed by Ceplecha, is characterized by a light curve with an abnormally steep rising branch. Attempts made to justify the observed shape and magnitude of the light curve with various ablation models, consistent with a nonfragmenting iron meteoroid, are unsuccessful. It is possible that the sodium-free meteoroids are derived from a source other than that which produces iron-nickel meteorites.

RÉSUMÉ

Des spectres de météores composés du spectre de radiation du fer, mais sans les raies D du NaI, ont été attribués dans le passé aux météores fer-nickel. Un tel exemple, un météore observé et analysé par Ceplecha, est caractérisé par une trainée lumineuse ayant une branche montant plus rapidement que la normale. Des essais pour expliquer la forme et la magnitude de la trainée lumineuse, en employant différents modèles d'ablation, en accord avec les météores ferreux non fragmentés, n'ont pas eu de succès. Il est possible que les corps sans sodium proviennent d'une source autre que celle qui produit les météorites fer-nickel.

КОНСПЕКТ

Метеорные спектры состоящие из **Fe** радиации, но без **D** линий **Na I**, были в прошлом приписываемы к железо-никелевым метеорным телам. В одном из таковых случаев, метеор наблюдаемый и анализированный Сеплешей был охарактеризован световой кривой с ненормально круто восходящей ветвью. Попытки сделанные для об'яснения формы и величины световой кривой для различных моделей абляции, совместимых с недробленным железным метеорным телом, являются неуспешными. Возможно что несодержущие натрий метеорные тела происходят из иного источника чем того который производит железо-никелевые метеорные тела.

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1. INTRODUCTION

The D-lines of Na I are the most pervasive characteristics of meteor spectra. They dominate the spectra for $\lambda > 5000$ Å in slow meteors and are an obvious feature in meteors of all velocities. This fact is a reflection of the fortunate circumstances that place a strong resonance line in the easily observable portion of the spectrum unobscured by other lines. Minute traces of sodium, less than 1% of the iron abundance and probably less than 0.1% of the meteor, are sufficient for this radiation to compete successfully with other species. Therefore, the absence of sodium D-lines suggests a remarkable purity that requires explanation.

Three modern meteor spectra (Halliday, 1960; Ceplecha, 1966; Barbon and Russell, 1967) offer examples of spectra without detectable sodium. Halliday's spectrum was readily accepted by most workers, including this author, as resulting from a "pure" iron-nickel meteoroid of origin similar to the material that produces meteorites. This assumption, which permitted one to accept as known quantities certain physical parameters of the meteoroid, led to a determination of the luminous efficiency of iron (Cook, Jacchia, and McCrosky, 1963). The value was in fair agreement with the data derived from an artificial iron meteoroid of similar size (McCrosky and Soberman, 1963).

The absence of sodium was equally striking in Ceplecha's excellent spectrum of Meteor 36221. Furthermore, this object entered the atmosphere at 32 km sec^{-1} — more than twice the velocity of Halliday's — and yet failed to produce any detectable radiation from Ca, Mg, Mn, Al, or Cr. All these

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elements had been observed previously in this velocity range. These elements, as well as sodium, are certainly underabundant in Ceplecha's meteoroid.

In this paper I investigate the observed luminosity characteristics of Meteor 36221 and attempt to find an ablation model for a strong (nonfragmenting) iron body consistent with these observations.

Meteor 36221 is, by casual inspection, a suspicious object. The descending branch of the light curve is abnormally steep for an object of this velocity, and the duration of the meteor, 0.6 sec, suggests that the light curve is greatly foreshortened compared to that expected for a nonfragmenting body.

2. MODEL I: CONSTANT SHAPE

We can determine an upper limit to the initial mass under the assumption that the body is meteoritic iron obeying the simple single-body meteor theory, and compare this mass with that obtained from the mass-luminosity relationship. The ablation equation,

$$\frac{dm}{dt} = -\frac{\Lambda}{2\zeta} \mathcal{A} \rho V^3 \quad , \tag{1}$$

gives the rate of mass loss, dm, for a body of the presentation area $\mathcal{A}$ moving through an atmosphere of density ρ at velocity V. The ablation energy per gram of material is given by ζ, and the efficiency of energy transfer from the air stream to the body is Λ. Meteor 36221 displays almost negligible deceleration, and, consistent with the quest for an upper limit, I assume the velocity to be constant and equal to the initial value. I further assume an exponential atmosphere of the form

$$\rho = \rho_0 \, e^{(H_0 - H)/\beta} \quad , \tag{2}$$

and an altitude-time relationsip given by

$$H = H_0 - Vt \cos Z_R \quad , \tag{3}$$

where H_0 is some appropriate reference height at the beginning of the visible trajectory, β is the atmospheric scale height, and Z_R is the trajectory angle measured from the vertical. The mass and area, $\mathcal{A}$, are related dimensionally by a shape-density factor A:

$$\mathcal{A} = A m^{2/3} \quad . \tag{4}$$

Equations (1) through (4) can be combined and integrated to give

$$m_0^{1/3} - m_1^{1/3} = \frac{\Lambda A\beta V^2}{6\zeta \cos Z_R} (\rho_1 - \rho_0) \quad , \tag{5}$$

where the subscript 0 refers to initial values and the subscript 1 to values at or near the end of the visible trajectory. To maximize the left-hand side of the equation, I choose $\Lambda = 1$. The effective heat-transfer coefficient can theoretically exceed unity by a small amount if an oxidation takes place on the surface. If this mechanism were in fact very efficient, the FeO radiation would appear in the spectra.

For ζ, I assume all mass loss by melting and spraying of droplets at the melting temperature. With an initial temperature of 270° K, a melting temperature of 1800° K, and Öpik's values (1958, p. 156) of the specific heat and heat of fusion of meteoritic iron, the minimum ablation energy is 1.33×10^{10} ergs g^{-1}. Assuming $A = 0.31$ (a value appropriate for a sphere of density 7.8 g cm^{-3}) and $\rho_0 = 0$ (to maximize the heating), I find for a point at the end of the visible trajectory (H = 72 km) that

$$m_0 = (m_1^{1/3} + 2.2)^3 \text{ g} \quad . \tag{6}$$

To determine the initial mass, m_0, we need an estimate of the terminal mass, m_1. Ceplecha's (1966) published light curve gives 0 mag for the luminosity at the point of disappearance. The artificial meteor experiments (McCrosky and Soberman, 1963) show that at about an altitude of 72 km the luminosity of a 2-g iron object will be at least 0 mag if the velocity is only 10 km sec^{-1}. Hence, 2 g is a very safe upper limit to the terminal mass, and we then have $m_0 < 33$ g. A more realistic value is obtained if we assume the terminal mass to be negligible, in which case $m_0 < 11$ g. Let us assume an ablated mass of 15 g for purposes of discussion. Can this mass produce the observed luminosity?

The luminous efficiency of iron in the meteoric process has been studied by a number of techniques, all of which show general agreement. However, these results are generally expressed as efficiencies for a particular broad wavelength region (detailed spectral data were not available) relative to the effective intensity of A0 stars. To convert Ceplecha's absolute line-intensity values to the photographic system, the intensity distribution of the star, $I^{*}(\lambda)$, and of the meteor, $I_m(\lambda)$, must be taken into account as well as the sensitivity of the film, $S(\lambda)$, and the absorption of the optical system, $T(\lambda)$.

$$M_{pg} = M_{*pg} - 2.5 \log \int_{\lambda} I_m(\lambda)\, S(\lambda)\, T(\lambda)\, d\lambda + 2.5 \log \int_{\lambda} I_{*}(\lambda)\, S(\lambda)\, T(\lambda)\, d\lambda \quad . \tag{7}$$

The values of I_m are taken from Ceplecha (1966), and of I_* from Strom, Gingerich, and Strom (1966) for the A0 star Sirius. The functions for $S(\lambda)$ and $T(\lambda)$ are appropriate for the Super-Schmidt system used (McCrosky and Soberman, 1963) to determine the luminous efficiency, τ_0, for iron; $S(\lambda)$ is given by the sensitivity curve for Eastman Kodak X-ray (blue-sensitive) emulsion, and $T(\lambda)$ by the transmission function of the Super-Schmidt optics as estimated by Harvey (1967). The $T(\lambda)$ is essentially the transmission curve of LF-5 glass, the limiting element in the Super-Schmidt correcting lens. The integration of equation (7) was performed by quadrature with steps of 100 Å. The photographic magnitude of the meteor at point J (see Ceplecha, 1966) is found to be $M_{pg} = -13.3$, or 3.1 mag brighter than Ceplecha's bolometric magnitude, M_{bol}, at this point. It is difficult to accept so large a color correction. Ceplecha (private communication) has determined a brightness of the meteor from direct photographs on panchromatic film and finds, at maximum light, that $M_{pan} \geq -11.0$. Although this value cannot be compared directly with M_{pg}, it appears safer to accept this value, which is independent of numerous intermediate steps required in spectral photometry. Accordingly, I have corrected all Ceplecha's published values of M_{bol} by -0.8 mag. The light curve can then be adequately described by the equations

$$M_{pg} = -1.9 - 13.3t, \qquad 0 \le t \le 0.55 \quad ,$$
$$M_{pg} = -11.0, \qquad 0.55 < t \le 0.60 \quad . \tag{8}$$

Then the photometric mass is found to be

$$m_{ph} = \frac{2}{\tau_0 V^3} \left(\int_0^{0.6} 10^{0.4M_{pg}} dt \right) = 135 \text{ g} \quad . \tag{9}$$

Had I used the correction implied by equation (7), the mass would be 1.1 kg.

The discrepancy between the photometric mass and the maximum ablated mass is about 1 to 2 orders of magnitude.

3. MODEL II: CONSTANT AREA

The above discussion was predicated on a spherical meteoroid. By assuming a body shape with the minor axis in the flight direction, $\mathcal{A}$ can be increased without limit. As an example of the flattening required to satisfy the observations, I choose a cylindrical section of radius, r, and thickness, L, ablating from the front surface only. The presentation area is $\mathcal{A} = \pi r^2 =$ constant. For this model we can derive an equation similar to equation (4), of the form

$$\frac{m_0 - m_1}{\pi r^2} = \frac{\Lambda\beta V^2}{2\xi \cos Z_R} (\rho_1 - \rho_0) = 21 \text{ g cm}^{-2} \quad , \tag{10}$$

where the right-hand side has been evaluated with the same values used previously. If $m_1 = 0$ and $m_0 = m_{ph} = 135$ g, then $r \approx 1.5$ cm and $L \approx 2.7$ cm.

This example is presented only to indicate the variations possible if one aspect of the usual single-body theory is relaxed. Nevertheless, such a shape and ablation process are not inconceivable. Indeed, this ablation process offers a qualitative explanation of some characteristics of Meteor 36221. The hypothetical meteoroid here considered would be expected to melt through and collapse near the end of its trajectory, producing a terminal flare. Furthermore, if the ablation process as proposed is effective in the early part of the trajectory, then the mass loss, and thus the intensity, should increase exponentially with time; i. e., the magnitude should decrease linearly with time, as observed. However, it is the failure of the constant-area ablation process to provide a quantitative prediction of the early part of the light curve that causes one to reject the model. The following proportionalities are evident in the equations governing the intensity, the mass loss, and the trajectory:

$$I \propto \dot{m} \propto \rho \propto e^{\frac{Vt \cos Z_R}{\beta}} \quad . \tag{11}$$

Converting to a magnitude scale, we find

$$M \propto bt, \text{ where } b = -4.1 \text{ mag sec}^{-1} \quad . \tag{12}$$

The actual light curve is described (equation (8)) by a slope of -13.3 mag sec^{-1} or a factor of 2.3 larger.

This degree of foreshortening of the trail is similar to that determined for Halliday's "iron" (Cook et al., 1963, p. 216), where it was found that the light curve could best be fit to a theoretical (single-body) curve if the atmospheric scale height were reduced by a factor of 4.3. In this case, the foreshortning can be understood if the body is sufficiently small to permit nearly complete melting before significant ablation occurs. A. F. Cook has pointed out to me that the same effect cannot explain the foreshortning of the Ceplecha meteor. This is certainly a larger body and the depth of heating, which depends inversely on velocity, is smaller. The delay of ablation resulting from the heat-sink will only be a skin effect.

4. MODEL III: INCREASING AREA

The constant-area ablation model can be replaced by one in which the area continually increases with time. This model is conceptually similar to that proposed by Allen and Baldwin (1967), in which a flange of material is built up by melt solidifying on the outer rim of the body. It is perhaps inconsistent to require both that the area is increased by solidifying the melt <u>and</u> that the ablation, by melting, increases as the area. But if such were the case, the ratio of the area at maximum light, A_{max}, and at the beginning of the meteor, A_0, for a cylindrical body would have to be

$$\frac{A_{max}}{A_0} = \frac{I_{max}\,\rho_0}{I_0\,\rho_{max}} \approx 10^2 \tag{13}$$

to conform with the observations. The model as proposed is unrealistic.

The observations and the preceding unsuccessful attempts to justify the initial assumption concerning the meteoroid structure are reminiscent of the observations and interpretations that led to the concept of structurally weak bodies (Jacchia, 1955). The anomalous deceleration, a function of the momentum transfer from the air stream to the meteoroid, was a dominant consideration there. The same general possibilities emerge when the iron meteor is analyzed in terms of the energy transfer.

A. The meteoroid is a typical iron meteorite type. If Model I is applicable, our present value of the luminous efficiency underestimates the true value by 1 or 2 orders of magnitude. A corollary to this is: the stony objects previously observed (Cook *et al.*, 1963) have an iron composition between 1 and 2 orders of magnitude less than the average stone meteorite. If Model I or II is accepted, the present theory of light production by meteors bears no resemblance to reality.

B. The meteoroid has the composition of a typical iron but was assembled, perhaps along with some impurities, into an extremely fragile structure.

C. The meteoroid is fragile. The origin of the meteoroid is not associated with iron meteorites and owes its composition and structure to some fractionation process operating during its formation. The iron need not exist in metallic form, nor are all other elements necessarily absent. Both silicon and oxygen may be present in large quantities and remain undetectable in the spectrum.

The third spectrum, obtained by Barbon and Russell (1967) on the 18-inch Schmidt, is of a meteor whose velocity and orbit are unknown. Unlike Ceplecha's meteor some elements other than iron are observed. The difference between their object and Ceplecha's may only be one of velocity and not of composition.

Of major concern, of course, is a source for these bodies. One can only eliminate the usual sources of meteorites as being unlikely. The physical characteristics are unlike those of iron meteorites. The absence of sodium and the apparent fragility rule out any normal stone meteorite. All shower meteors, those definitely associated with comets, show sodium in their spectra as do the comets themselves on many occasions. While one cannot rule out some special meteorite source or some special comet, this suggestion begs the question.

While source is the major problem, these data do introduce two minor considerations into the physical theory of meteors. Inevitably some suspicion is now attached to our earlier analysis of the Halliday iron meteor. However, its weight in the value of the coefficient of luminous efficiency, τ_0, generally used today is small so that problem is academic. Second, if sodium-free meteors represent 1% of the meteor population, which the present observations suggest, and if sodium and other underabundant elements are predominant producers of electrons in the ion column formed by meteors, as suggested by Lazarus and Hawkins (1963), then one may expect an occasional abnormally long but faint radar meteor caused by these strange objects.

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BIOGRAPHICAL NOTE

Dr. Richard McCrosky holds joint Smithsonian-Harvard appointments as Astronomer, Smithsonian Astrophysical Observatory, and Research Associate, Harvard University. He is also Scientist-in-charge of the Smithsonian's optical meteor projects. His primary research specialties include photographic and spectral meteor studies.

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